# Optimising Demand and Bid Matching in a Peer-to-Peer Energy Trading Model

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***Abstract*— This paper addresses Peer-to-Peer energy trading as one of the new market paradigms for the post-subsidy operation of distributed renewable energy sources in local energy networks. The owners of such facilities become prosumers and now play an active role in the local energy supply by trading electricity among each other. This paper proposes: 1). an internal pricing model among peers by using the supply-demand ratio; 2). a peer self-optimisation method for promoting self-consumption of renewable energy; and 3). a peer to peer optimisation method that matches prosumer peers by reducing the distances of their energy trading. The case study validates the effectiveness of the proposed Peer-to-Peer trading method with real data. The main improvements revealed are significant economic benefits for the community and prosumers, i.e., a lower exchange of electricity with the utility grid by increasing the self-consumption in the community, and a reduction of peak demand hours due to local energy trading.**

***Keywords*— Demand Shifting, Distributed Renewable Energy Sources Internal Pricing Scheme, Peer-to-Peer energy trading, Prosumer***

## I. Introduction

THE energy sector is under major reconstruction due to the ambitious goals set by many countries to reduce their carbon dioxide emissions in the coming decades. One of the emerging developments within this sector is the increasing share of distributed renewable energy sources (DRES). DRES are small residential generation facilities based on renewable resources. Solar panels dominate, but small wind turbines and micro-combined heat and power (mCHP) applications are also being installed in households and small businesses. The owners of such facilities are transformed from consumers to prosumers and now play an active role in the local energy supply [1].

DRES systems bring many advantages compared to a centralised supply from large power plants. Electricity is consumed in close proximity to generation and not fed into the transmission grid, therefore reducing transfer losses and high fluctuations associated with the grid. However, it also provides new challenges to the power system, and so-called "smart grids" are required to actively control decentralised generation. They differ from the traditional grid through the implementation of a two-way communication system which enables the exchange of information in both directions [2]. This introduces the second major development in the energy sector, the deployment of information and communication technology (ICT). ICT is a fast-developing field, which provides important services to the energy sector. In order to optimise operations, a smooth integration of DRES continuous monitoring and remote-control is crucial, which is made possible by ICT.

Previously renewable electricity feed-in tariffs (FIT) were used to determine the expansion of generation facilities on a residential level. These tariffs are decreasing due to the increasing share of DRES and the fall in prices of renewable generation applications [3]. During the next years, the operation of such facilities without subsidies will be commonplace in most countries and therefore must be profitable. A possible solution for the post-subsidy operation is peer-to-peer (P2P) energy trading, which enables the trade of electricity among prosumers and consumers. This market construct can make a third-party entity redundant, such as a retailer that only buys electricity to later sell it on. P2P energy trading has the potential to become a cheap way to share electricity locally, while also facilitating the expansion of microgrids (MG) around the world [4].

There are seven key components of microgrid markets to efficiently trade energy in a P2P manner [2][5]:

The *market setup* defines the participants, and the form of energy traded. The existing literature has some variation on who participates in P2P energy trading. Prosumers are introduced to P2P energy trading as entities that can shift their roles between generators and consumers as described in [6]. In [7] and [8] plug-in (hybrid) electric vehicles (EVs) are acting as peers that trade electricity among each other in order to balance the local electricity demand and reduce the impact of the charging process on the power system.

Nearly all P2P energy trading models in the literature propose a microgrid that has a *grid connection*. This link to the utility grid is essential to exchange energy in times of imbalance in the subsystem [9]. The *information system* provides a connection between market participants and access to the market platform and monitors the operation. Several papers discuss blockchain as a suitable technology to conclude smart contracts between peers [7] [10].

The *market mechanisms* main purpose is to match buying and selling orders of the peers by defining the market allocation principle, payment rules, and bidding format. According to [4], the market mechanisms proposed in the literature can be classified into three different models, which differ in the way they are reaching the optimal allocation: auction model, multi-agent model, and analytical model.

As part of the allocation principle, the *pricing mechanism* is important to balance supply and demand in the system. Three different approaches, bill sharing model (BS), mid-market rate and supply and demand ratio (SDR) have been used in existing pricing schemes. Reference [11] rates those methods by their efficiency and concludes that BS is the most inefficient as it does not provide enough incentives for all participants to trade in a P2P matter.

An *energy management system* (EMS) is crucial when participating in a P2P energy trading zone. It predicts and analyses the supply and demand in real-time to identify the correct amount of electricity to be traded. An EMS becomes more active if the P2P energy trade is combined with a demand response optimisation as proposed by [12].

*Regulations* determine the implementation of P2P trading into existing energy markets, the market design and how fees and taxes are distributed. "Regulatory sandboxes", where new ideas can be tested without strict requirements are recommended by [13], whilst [14] perceives the lack of regulatory and legislative transparency as a main barrier to further implementations.

Up until now, existing P2P energy trading research has largely focused on aforesaid seven solos, but lack of whole system thinking. This paper first links *pricing mechanism, energy management system, grid connection, and market mechanisms* together to develop a whole system framework. The detailed contributions are:

- A new internal pricing method is proposed that builds on supply-demand ratio method;
- A peer's self-optimisation method is proposed to maximise self-consumption and minimise energy exchange with the utility grid;
- A peer to peer optimisation method is developed that automatically matches prosumer peers with reduced trade distance.
- Real data is used to validate the proposed framework and investigate the benefits to multiple market actors.

The paper is organised as follows: Section II explains the P2P trading model. The internal pricing scheme and the cost function are explained as part of the two-stage optimisation. This is followed by a case study in Section III, which illustrates the results of the model and outlines the benefits of P2P energy trading. Section IV concludes the main aspects of the paper and gives an outlook on future research.

## II. P2P TRADING MODEL

### A. Principles of the model

The objective of the optimisation model proposed here is to minimise the electricity bill of the community. In order for the model to be successful, the resulting P2P trading must be beneficial for everyone. Some prosumers benefit more than others, depending on the willingness to adjust the demand and technical availability of shift-able devices, such as dish washer and washing machine, but the model does ensure that everyone benefits financially from participating in the trade. Another relevant factor for the individual profitability of P2P trading is the time in which the generation facilities produce electricity. If the production of a prosumer complements the majority they will profit more, as the availability of electricity in the system determines its price.

The minimisation of the community electricity bill is conducted in two stages. The first stage optimises the load of the prosumer (a peer) and thus creates individual benefits for every participant, while the second stage improves the situation for the whole community. P2P optimisation matches trading peers that are closest to each other and thereby reduces power losses in the system. This improvement lowers the cost for the distribution system operator (DSO), who pays less for grid stabilisation methods. Lower network charges can be applied, by reducing the cost of the system operation, which benefits the whole community.

Instead of a third-party entity, as suggested in other papers, a cloud solution could automatically collect and analyse data from the individual EMSs. The cloud uses the optimisation model proposed to obtain the information on load scheduling and electricity exchange of the prosumers and returns it to their EMS. The EMS then automatically controls all smart devices within the load of the prosumers. Figure 1 shows a possible setup for a grid-connected P2P trading network. Different peers, including residential apartment buildings or single-family houses, research institutions or commercial buildings can participate in the P2P energy trading. The only obligatory requirements to participate are an EMS and a smart meter, but they do need to be equipped with a grid-connected generation facility in order to sell electricity in the system. Energy storages are not considered in this model.

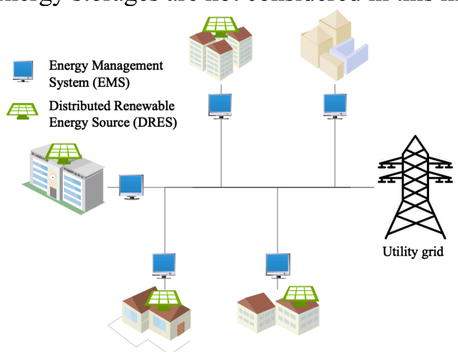



*Fig. 1: P2P energy trading network*

### B. Prosumer data

The participants in the P2P trading model are hereinafter named as prosumers. For the case that a participant does not have its own DRES, it simply becomes a prosumer with a generation of zero for every time interval. It is also assumed that every participant is able to shift a certain amount of its loads.

For Optimisation 1, the following information needs to be known for every prosumer. The original electricity consumption (*TP*) and production (*P*) from DRES for every time interval in a day:

$$TP_i = [TP_i^1, \dots, TP_i^H] \tag{1}$$

$$P_i = [P_i^1, \dots, P_i^H] \tag{2}$$

$$i \in \{1, \dots, n\},\ h \in \{1, \dots, H\}$$

Where $n$ is the number of prosumers participating in the P2P energy trading and H is the amount of time intervals. With this data, the net power value (*NP*) for every time interval in the system can be determined. A positive value indicates a demand for electricity, a negative value for *NP* implies a surplus for prosumer $i$ in time interval $h$.

$$NP_i^h = TP_i^h - P_i^h \tag{3}$$

### C. Internal pricing

The internal pricing scheme uses the information of power availability in the system to define the total buying power (*TBP*) and total selling power (*TSP*).

$$TBP^h = \sum_{i=1}^{n} NP_i^h, \quad NP_i^h \geq 0 \tag{4}$$

$$TSP^h = -\sum_{i=1}^{n} NP_i^h, \quad NP_i^h < 0 \tag{5}$$

To determine a price, the supply-demand ratio (*SDR*) is used as a market indicator. The *SDR* is a useful market instrument to control the availability of a good. In this case, the price is used as an incentive to shift the load from time intervals with high demand to times with lower demand.

$$SDR^h = TSP^h / TBP^h \tag{6}$$

A difference between this market and usual markets is that there is rarely an equilibrium in the submarket. Either prosumers produce too much electricity or demand more than they produce. Then a trade with the main grid has to balance the system. Therefore, prices in the system must cover the cost for trading within the system plus the electricity exchange with the utility grid. To receive a fair distribution, everyone in the system gets the same price in a specific time interval. However, there are two prices, one for selling ($Pr_{sell}$) and one for buying ($Pr_{buy}$) electricity.

We use the function of inverse proportion to define $\mathrm{Pr}_{\mathrm{sell}}$. When the amount of electricity produced in the system is greater than the demand, equally speaking $SDR > 1$, surp is electricity is sold to the main grid. The main grid buys electricity for the country-specific feed-in-tariff (FIT), here defined as $\lambda_{sell}$. If $SDR = 0$ no prosumer can sell electricity, therefore, the price to buy electricity must be equal to the one of the grid, $\lambda_{buy}$. This leads to the following selling price function:

$$\mathrm{Pr}_{sell} = f(SDR) = \begin{cases} (\lambda_{sell} \cdot \lambda_{buy}) / ((\lambda_{buy} - \lambda_{sell}) \cdot SDR + \lambda_{sell}) & for\ 0 \leq SDR \leq 1 \\ \lambda_{sell} & for\ SDR > 1 \end{cases} \tag{7}$$

In the case of $Pr_{buy}$ [15] derives the price function from the equation of the economical balance in the system.

$$TBP \cdot \mathrm{Pr}_{buy} = TSP \cdot \mathrm{Pr}_{sell} + (TBP - TSP) \cdot \lambda_{buy} \tag{8}$$

Replacing *TBP* and *TSP* by *SDR* gives the buying price function:

$$\mathrm{Pr}_{buy} = f(SDR) = \begin{cases} \mathrm{Pr}_{sell} \cdot SDR + \lambda_{buy} \cdot (1 - SDR) & for\ 0 \leq SDR \leq 1 \\ \lambda_{sell} & for\ SDR > 1 \end{cases} \tag{9}$$

### D. Cost function

In this model, two relevant parameters determine the cost function for every prosumer. First, the cost for consumed electricity in a specific time interval, which can also be negative if electricity is sold. The other part is the cost of the inconvenience caused by adjusting the loads. Every prosumer has a different sensitivity regarding the inconvenience caused by shifting the demand. Therefore, the model includes an inconvenience coefficient $\alpha_i$ for every prosumer. This is a value every prosumer chooses regarding their preferences. The amount of adjusted electricity multiplied by $\alpha$ makes up the second part of the cost function. The optimised electricity consumption of prosumer *i* after adjusting the load is defined by $x_i$.

$$\alpha_i = \begin{bmatrix} \alpha_1 \\ \vdots \\ \alpha_n \end{bmatrix} \tag{10}$$

$$x_i = [x_i^1, \ldots, x_i^H] \tag{11}$$

$$C_i^h(x_i^h) = \mathrm{Pr}_i^h(x_i^h - P_i^h) + \alpha_i (x_i^h - TP_i^h)^2 \tag{12}$$

### E. Self-Optimisation of A Peer

In the first stage, the demand for the prosumers is optimised using (15) to increase self-consumption and decrease the exchange of electricity with the utility grid. The following two constraints must be set to keep the load adjustment at a feasible level:

$$\sum_{h=1}^{H} x_i^h = \sum_{h=1}^{H} TP_i^h \tag{13}$$

$$\min(TP_i) \leq x_i^h \leq \max(TP_i) \tag{14}$$

As the optimisation is only an adjustment not a reduction of load, the total demand over a day must be equal, therefore constrained by (13). The second constraint (14) is ensuring that the new load is limited between the baseload and maximum load of prosumer *i*.

$$\begin{aligned} & \min C_i(x_i, \mathrm{Pr}_i) = \\ & \sum_{h=1}^{H} (\mathrm{Pr}_i^h (x_i^h - P_i^h) + \alpha_i (x_i^h - TP_i^h)^2) \\ & s.t. \quad (13) \\ & \qquad\quad (14) \end{aligned} \tag{15}$$

### F. Peer to Peer Optimisation

The second optimisation aims to match buying and selling peers in the system. The trading quantities determined in the first stage will now be allocated optimally. Optimising the allocation means reducing the physical distances that electricity has to travel between the trading peers. Distance, in this case, is the length of the electrical wires between the houses. It is assumed that power losses are proportional to distance and thus if peers that are closer to each other exchange electricity, losses can be decreased. The array of peers is shown in Fig. 2.

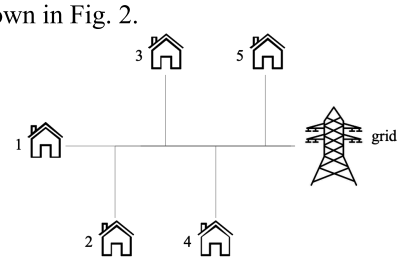



*Fig. 2: Array of prosumers*

According to this scheme, a distance matrix has been created, expressed as *D*. The elements of the matrix are not showing the actual electrical wire distances between peers but their order. For this stage the grid has to be treated as a peer, defined as *G*. The number of participants has now increased to $n' = n+1$.

$$D = \begin{array}{c} \\ P_1 \\ \vdots \\ P_n \\ G \end{array} \begin{array}{c} \begin{array}{cccc} P_1 & \cdots & P_n & G \end{array} \\ \begin{pmatrix} D_{11} & \cdots & D_{1n} & D_{1G} \\ \vdots & \ddots & \vdots & \vdots \\ D_{n1} & \cdots & D_{nn} & D_{nG} \\ D_{G1} & \cdots & D_{Gn} & D_{GG} \end{pmatrix} \end{array} \tag{16}$$

The output of P2P Optimisation is the trading matrix $y_{ij}$, which defines the quantity of electricity traded between peers. It can later be used to issue the transaction between them and the grid. Two constraints must be set when minimising the distance of the energy flow. Every peer can only sell as much electricity as it has as a surplus (19). Secondly, peers can only buy the amount of electricity, they require in a specific time interval, as they are not able to store it for later consumption (20). With these limitations, the trading matrix $y_{ij}$ is optimised the following way:

$$y_{ij}^h = \begin{pmatrix} y_{11} & \cdots & y_{1n'} \\ \vdots & \ddots & \vdots \\ y_{n'1} & \cdots & y_{n'n'} \end{pmatrix} \quad (17)$$

$$i, j \in \{1, \ldots, n'\}$$

$$\min E(y_{ij}^h) = \sum_{h=1}^{H} D \cdot y_{ij}^h \quad (18)$$

$$s.t. \quad \sum_{i=1}^{n'} y_{ij}^h = NP_j^h, \; NP_j^h < 0, \; for\ 1 \le j \le n' \quad (19)$$

$$\sum_{j=1}^{n'} y_{ij}^h = NP_i^h, \; NP_i^h \ge 0, \; for\ 1 \le i \le n' \quad (20)$$

$$for\ 0 \le h \le 24$$

## III. Case Study

### A. Data and Scenarios

This section presents a numerical analysis of the P2P trading model proposed in section II with real data. The input data for the simulation was provided by the German company Oxygen Technologies. As previously mentioned, Oxygen Technologies is operating a platform that enables P2P energy trading between prosumers. The study uses a network setup as smart grid, enabling two-way communication and remote control of devices and generation facilities for all participating peers.

Two different scenarios are tested in the model, which differ by the combination of peers and generating facilities. In Scenario 1, all of the five peers are equipped with a photovoltaic system (PV). Scenario 2 has a variation in the generation applications as it includes three peers with micro combined heat and power systems (mCHP) and thus different production profiles. The difference input data of the two scenarios is visible in Fig. 3 and Fig. 4. Every peer has their individual preferences and load shifting abilities and therefore a different inconvenience coefficient. A lower value of $\alpha_i$ represents less rejection towards adjusting the electricity demand. The input parameters for a typical day for the prosumers in scenario 1 and 2 are displayed in TABLE I.

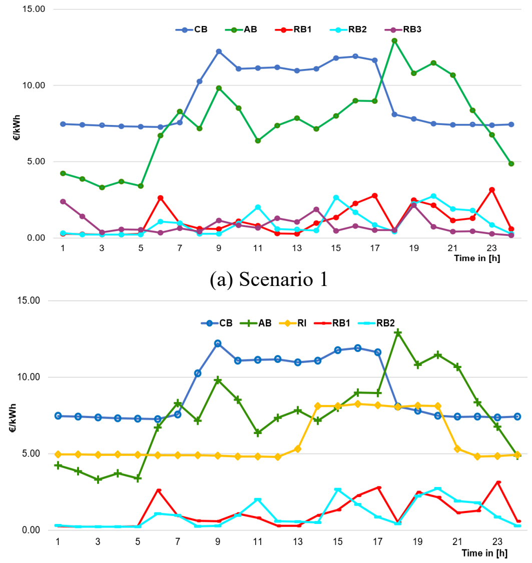
The selling price, equalling $\lambda_{sell}$ in the model, is based on the German feed-in tariff for distributed electricity of 10.74 (ct/kWh) for applications installed after 1st of July 2019 [16]. For the price for buying electricity from the utility grid, the German average price for electricity from 2018 of 29.88 (ct/kWh) is taking for $\lambda_{buy}$ [17].

### B. Results

By using the optimisation an adjustment is completed to the load of the prosumers. The demand rescheduling leads to new net power curves which are shown in Figure 5 as an aggregate of the five peers in the community. Hours of negative net power curves, as well as the demand peaks, are reduced in both scenarios. Figure 6 shows the internal price curves for the P2P trading zone based on which the load scheduling has been carried out. Scenario 2 displays more volatility, especially in the selling price compared to the price curves in the first scenario.

TABLE I. Input parameters for prosumers in scenario 1 and 2

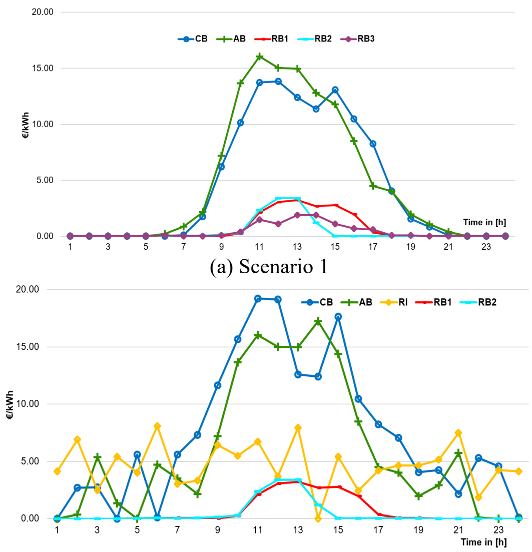
| peers | [ID] | distributed generation application | daily consumption in [kWh] | inconvenience coef. $\alpha_i$ |
|---|---|---|---|---|
| **scenario 1** | | | | |
| *Commercial Building* | *CB* | PV | 218.2 | 0.01 |
| *Apartment Building* | *AB* | PV | 179.8 | 0.015 |
| *Residential Building 1* | *RB1* | PV | 27.4 | 0.05 |
| *Residential Building 2* | *RB2* | PV | 24.1 | 0.04 |
| *Residential Building 3* | *RB3* | PV | 20.2 | 0.06 |
| **scenario 2** | | | | |
| *Commercial Building* | *CB* | PV, mCHP | 218.2 | 0.01 |
| *Apartment Building* | *AB* | PV, mCHP | 179.8 | 0.015 |
| *Research Institute* | *RI* | mCHP | 141.1 | 0.07 |
| *Residential Building 1* | *RB1* | PV | 27.4 | 0.05 |
| *Residential Building 2* | *RB2* | PV | 24.1 | 0.04 |



(a) Scenario 1

(b) Scenario 2

*Fig. 3: Prosumer's load profiles*

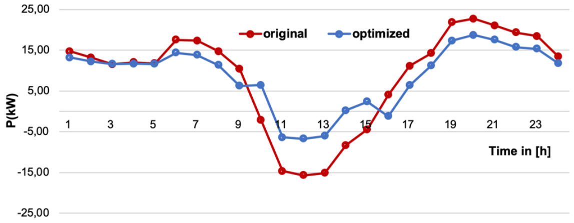


(a) Scenario 1

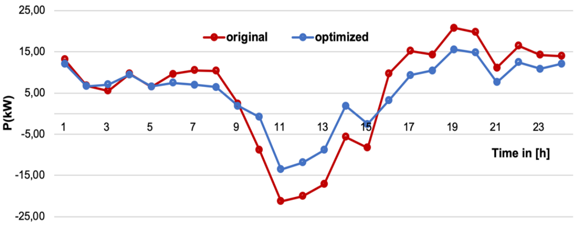
(b) Scenario 2

*Fig. 4: Prosumer's generation profiles*

On the base of the new demand profiles and the conducted P2P trade, new electricity bills are displayed. The original bill is calculated with the average electricity price in Germany and the feed-in tariff as described earlier. For the P2P trading case the internal prices, as shown in Figure 6, are the basis of the bill calculation. TABLE II shows a comparison of the original bills and the new cost for electricity in the community. A reduction of 28.94% in the electricity bill of the community is achieved for the second scenario. It is also visible that in both scenarios not only the overall electricity bill of the community improved but every participant's bill as well.



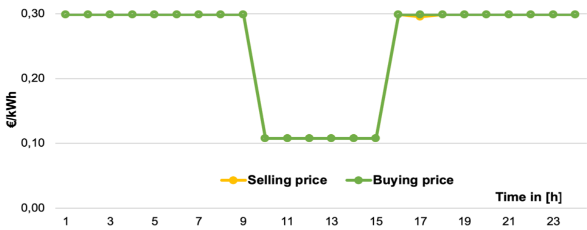

(a) Scenario 1




(b) Scenario 2

*Fig. 5: Net power curves of the community*

Another result, illustrated by TABLE III is a lower exchange of electricity with the utility grid. Both scenarios reduce their trade with the main grid significantly. In scenario 2, 346.08 kWh have been traded with the main grid in a typical day. Participating in the P2P energy trading model decreased the exchange by 42.13% through sharing the excess electricity locally. The original exchange is the demanded electricity from the utility plus the one fed into the grid by the distributed generation applications.




(a) Scenario 1


(b) Scenario 2

*Fig. 6: Internal price curves*

TABLE II. ELECTRICITY BILL OF THE COMMUNITY

| peers | | original in [€] | P2P in [€] | improvement in [%] |
|---|---|---|---|---|
| **scenario 1** | [ID] | | | |
| *Commercial Building* | *CB* | 34,52 | 33,21 | -3,81% |
| *Apartment Building* | *AB* | 26,78 | 21,84 | -18,43% |
| *Residential Building 1* | *RB1* | 5,12 | 3,60 | -29,60% |
| *Residential Building 2* | *RB2* | 5,16 | 3,28 | -36,56% |
| *Residential Building 3* | *RB3* | 3,64 | 2,51 | -31,04% |
| *Community* | | 75,21 | 64,43 | -14,33% |
| **scenario 2** | | | | |
| *Commercial Building* | *CB* | 18,24 | 15,87 | -12,98% |
| *Apartment Building* | *AB* | 21,25 | 14,77 | -30,47% |
| *Research Institute* | *RI* | 11,91 | 7,54 | -36,71% |
| *Residential Building 1* | *RB1* | 5,38 | 3,55 | -34,06% |
| *Residential Building 2* | *RB2* | 5,34 | 2,41 | -54,87% |
| *Community* | | 62,11 | 44,14 | -28,94% |

TABLE III. EXCHANGE OF ELECTRICITY WITH THE UTILITY GRID

| | original in [kWh] | P2P in [kWh] | reduction in [%] |
|---|---|---|---|
| **scenario 1** | 341,99 | 249,95 | 26,91% |
| **scenario 2** | 346,08 | 200,27 | 42,13% |

## C. *Discussions*

The results of the case study demonstrate that the P2P energy trading model could bring significant economic benefits to the community and individual prosumers. Thus, it is proven that every prosumer benefits financially when participating in P2P trading than before. This is a crucial criterion to consider when contemplating an expansion in the number of participants in an energy community and necessary to increase the spread.

The reduction in electricity exchange with the utility grid, as illustrated in TABLE III, is caused by a higher self-consumption of distributed generated electricity within the community and a decrease in demand during peak hours. Lower peak demand and less fluctuation in the grid, visible in the comparison of net power curves in Figure 5, is beneficial for the DSO, as it decreases the work to balance the grid and reduces the need for grid expansion. This study assumes that the DSO is responsible for the stabilisation of the microgrid and the balance with the main grid, this could also be a different service provider for the control of microgrids. Reducing their work would ultimately lower network charges, thereby benefiting the whole community.

The simulation has been carried out using two scenarios to test the effect of peer variation on the model. Scenario 2 has a higher variety of peers and differences regarding their generation profiles. This is visible in Figure 4, showing the production profiles for the scenarios. The results displayed in TABLE II and III, illustrate that lower homogeneity in peers and production leads to a higher reduction in energy bills and a greater decrease in electricity exchange with the utility grid. Complementary generation and load profiles enable more self-consumption and decrease the number of demand peak hours. This work suggests that connecting diverse peers using microgrids can significantly enhance the benefits of P2P energy trading.

The proposed model uses three changeable parameters: The individual generation and load profiles, the selling and buying price to the grid, and the inconvenience coefficient. Each of the parameters depends on the individual settings, the users' preferences and the electricity market of the area being simulated. Therefore, the results can only be used to show a general direction, and are not universally applicable.

Further considerations have to be taken to make the simulation more realistic in future work, as it does not show all the effects of P2P energy trading. A useful addition would be the implementation of physical network constraints in the optimisation model as done by [9]. Currently, every trade in the system is sanctioned, even if it exceeds network limits. As trading in the system is being conducted without a third party, the transaction cost is minimised. Nevertheless, the physical trade of electricity causes losses which have so far been neglected in the model. The cost of losses and maintenance of the system should be internalised in further expansions of the model.

Further papers which test the implementation of P2P energy trading networks, could focus on the cost analysis between building a separate microgrid or using the existing distribution grid. Network charges contribute a large proportion of the cost for electricity in many countries, hence an independent microgrid could be a more cost-effective option, but the cost of maintenance and main grid balancing have to be included.

Introducing energy storages into the model would allow an adjustment on the supply side as well. Prosumers could use hours of low internal pricing to fill their storages and later use the energy through batteries and for heating water tanks during low generation periods. Another possible form of energy storage is electric vehicles. They could act as a battery when they are connected to the smart home system, and also deliver electricity to other peers when they are changing location during the day. This idea has been discussed by [8] but could be analysed in a combination with this model.

## IV. Conclusion

In this study, a model for the trade of electricity between prosumers in a P2P system has been proposed. This included a demand self-optimisation with an internal pricing model and a minimisation of the electricity flow through optimised peer-to-peer matching. The simulation utilised real data to validate the effectiveness of the model and revealed various benefits from P2P trading: (i) a lower electricity bill for every participant; (ii) reduced electricity exchange between the P2P community and the utility grid; (iii) a decrease in hours of peak demand.

There are several options to extend the current model that would make it more realistic. The implementation of physical network constraints and the internalisation of cost for losses and maintenance of the grid are important considerations. Including energy storage systems would allow an adjustment on the supply side as well, which could enhance the optimisation of the model. There are not only technical barriers that hinder a widespread implementation of P2P trading systems, as legislative regulations are the major hurdles for P2P trading projects in most countries.

## Acknowledgment

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